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. Project Description:

The primary goal of STAR's research program is to enhance our knowledge of the properties of the strongly interacting quark-gluon plasma (QGP) and to illuminate the roles of orbital motion and quark/anti-quark/gluon polarization in generating the spin of the proton. STAR has led the RHIC program in a three-year campaign on heavy-flavor physics as probes of QGP properties, our group has a leading role in the installation and commissioning of the Heavy-Flavor Tracker (HFT) and Muon-Telescope Detector (MTD) as well as the analysis of data from runs14, 15 and 16. The study of forward tagged proton studies (p+p elastic scattering and diffractive physics events) to investigate hadronic interactions dominated by gluons was begun in FY15. The group is focusing in the near future on preparations for the search of the QCD critical point. Members of the STAR research group are playing a leading role in efforts to realize an Electron-Ion Collider (EIC) in the US by performing studies to further strengthen the scientific case as well as in designing appropriate instrumentation to realize those physics opportunities.

19. Principal Investigator:

Signature(s) — Date: 7/28/16

STAR Research Group

The primary scientific focus of the STAR research program is to determine the properties of the strongly interacting quark-gluon plasma (QGP) discovered at RHIC and to fully delineate the roles of orbital motion and quark and gluon polarization in generating the spin of the proton. Future scientific opportunities at RHIC that the group is preparing for are the search for a possible QCD critical point, and forward tagged proton studies ($p+p$ elastic scattering and diffractive physics events) to study hadronic interactions dominated by gluons. In the long term, some members of the STAR research group are playing a leading role in articulating the compelling physics opportunities at a future Electron-Ion Collider (EIC) as well as the design of appropriate instrumentation to realize those opportunities.

An important role of the STAR research group is to provide scientific leadership to the STAR Collaboration as a whole. This is carried out formally through the efforts of several group members including Spokesperson (Zhangbu Xu, elected 02/17/2014), STAR Physics Working Group Co-Convenors Ultra-Peripheral Collisions (Wlodek Guryn), Heavy Flavor (Rongrong Ma), Upgrades Coordinator (Flemming Videbaek), Trigger Board (J.H Lee, chair), and Beam Energy Scan (BES) Focus Group (Paul Sorensen, leader). Previously, members of the STAR research group have also been Co-Convenors of the Heavy Flavor, HBT, Spectra, Light Flavor Spectra, Bulk Correlations, and Strangeness physics working groups. Informally, leadership of the STAR scientific program is achieved through the efforts of other members of the STAR research group who play leading roles in specific areas of the STAR scientific program (light flavor spectra, bulk correlations, jet-like correlations, heavy flavor, spin, and ultra-peripheral collisions). Paul Sorensen also served as chair of the Chiral Magnetic Task Force, reporting to Nuclear and Particle Physics Program Advisory Committee.

The group is the major driving force in upgrading the inner Time Projection Chambers (iTPC) sectors. We have spearheaded the development of an upgrade program to replace the inner sector of the STAR TPC for BES II project manager (Flemming Videbaek), developed and carried out simulations (Irakli Chakaberia), performed measurements on strong backs and compared with models (Robert Pak), and designed the readout electronics.

The group is the leading contributor in developing and operating the High Level Trigger (HLT). We plan to extend the online HLT farm with ~10 more high performance servers. Software-wise, in collaboration with the Frankfurt Institute for Advanced Studies (FIAS) group, we are exploring tracking with Cellular Automaton on STAR's HFT hits, as well as the associated online calibrations for the HFT. We also integrated the Muon Tracker Detector (MTD) information into the HLT and hopefully we can implement the HLT based triggers into the MTD program. (Aihong Tang, Hongwei Ke).

Members of the STAR group (J.H. Lee), led by Thomas Ullrich (co-chair of the EIC Task Force), have been actively participating in the EIC task force. Major contributions include di-hadron correlations, F2/FL, and diffractive processes. Ullrich also coordinates the EIC detector R&D program.

Technical Progress in FY 2016

Data from run 14 on Au+Au collisions at 200 GeV and 14.5 GeV has been analyzed with emphasis on heavy-flavor probes to study in detail the properties of the QGP and to continue the search for the critical point as we complete our phase I of the RHIC Beam Energy Scan. In addition, data from run 12 on *p+p* at $\sqrt{s}$=200 GeV, and U+U collisions has been analyzed extending our baseline statistics substantially beyond that gathered in run 9. Studies in U+U collisions allow us to investigate the influence of novel geometries on the evolution of the plasma. Most notably, the group has found and published hints of the existence of a Chiral Magnetic Wave formed in Au+Au collisions. Systematic studies over an unprecedented wide range of beam energies has revealed exciting features in the dilepton mass spectra as well as in J/ψ. The group is the major driving force in the upgrade of the inner TPC sectors. It contributes substantially to the BNL Electron-Ion Collider (EIC) task force to further strengthen and expand the compelling science which can be accomplished with a future EIC and to identify and address R&D which will need to be accomplished prior to developing a conceptual design for an EIC detector.

To date STAR has published: 2 Physical Review Letters, 1 Physical Review C papers, and 1 Physics Letters, and a total of 2 submitted papers in FY16.

"Energy dependence of acceptance-corrected dielectron excess mass spectrum at mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}}$ = 19.6 and 200 GeV", Phys. Lett. B 750 (2015) 64-71. (L. Ruan)

"Azimuthal anisotrophy in U+U and Au+Au collisions at RHIC", Phys. Rev. Lett. (2015), 222301. (J. Dunlop, H. Ke, P. Sorensen)

"Measurement of interaction between antiprotons", Nature 527 (2015) 345. (A. Tang)

"Beam energy dependence of the third harmonic of azimuthal correlations in Au+Au collisions at RHIC", Phys. Rev. Lett. 116 (2015) 112302. (P. Sorensen, H. Wang)

"Forward-backward multiplicity fluctuation and longitudinal harmonics in high-energy nuclear collisions", Phys. Rev. C 93 (2016) 044905. (Jia)

"Jet-like correlations with direct-photon and neutral-pion triggers at $\sqrt{s_{NN}}$ = 200 GeV", accepted, Phys. Lett. B. (J. Dunlop)

"Direct virtual photon production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV", submitted to Phys. Lett. B, (R. Ma, L. Ruan, S. Yang)

"J/ψ production in 39, 62.4 and 200 GeV Au+Au collisions" submitted to Phys. Lett. B. (L. Ruan)

"Analysis of the dielectron at low and intermediate mass from Au+Au collisions at 27, 39, and 62.4 GeV". In GPC review process (L. Ruan).

Anticipated Progress in FY 2017:

One major focus of the STAR group will be to analyze data taken in runs 14, 15 and 16 with MTD and HFT completely installed. The group will continue the physics analysis of the large data sets of Au+Au that are currently being reconstructed with focus on J/ψ production, and the first Υ measurement with dimuons. New opportunities are explored in the analysis of large data set utilizing the Roman Pots in $p+p$ and p+Au for both, diffractive and elastic processes.

The group is the major driving force in the upgrade of the inner TPC (iTPC) sectors. This upgrade has been approved as a capital equipment project by BNL/DOE and by the Chinese NSF and MoST agencies. The iTPC group is preparing for construction of the detector with major contributions from our group on management, mechanics, electronics, and simulations. The group will also continue to contribute to BNL's EIC efforts. This includes further expanding the physics case, detector design, as well as physics guidance for the cost and performance optimization of the machine design for a successful campaign to host an EIC at BNL and prepare the foundation for a DOE Critical Decision (CD-0) to initiate a construction project.

The group will continue in operating, developing, and improving the HLT, with focus on adding the data of the HFT and MTD and, if possible, on reconstructing secondary vertices by deploying massive parallel computing techniques.

Further goals are:

- Continue analysis of results from runs 14, 15 and 16 data from the MTD upgrade and HFT for STAR.

- Further publication of results from the first phase of the Critical Point search in runs 10, 11 and 14, including publication of v_n-observable.

- Simulation of key signatures for the STAR high-luminosity physics program and development of corresponding triggers where possible.

- Management of the iTPC project and start of construction.

- Organize scientific working groups and workshops such as chiral magnetic effect and long-range rapidity correlations in heavy ion collisions.

- Simulation and design studies documenting the physics program and technical realization for a future EIC facility.

- Continued scientific leadership in STAR by members of the group including co-convenorship of 2 of the 6 STAR Physics Working Groups as well as the STAR Spokesperson, Future Upgrades Coordinator, and Beam Energy Scan Focus Group Leader, and project leadership in the HFT, MTD, and HLT.

Researches breakout in details by topics:

1) Correlations and Fluctuations Related to the Initial Condition in Heavy Ion Collisions

The BNL STAR group is pioneering analysis methods to help STAR realize the goals laid out in the NSAC long-range plan, particularly determining the temperature dependence of the transport properties and pinning down the role of the chiral magnetic effect in heavy ion collisions. Group members have exploited three-particle azimuthal correlations to map out the three-dimensional nature of the initial state in heavy ion collisions and to help constrain the shear viscosity to entropy ratio (η/s) with a greater precision than the conventional measurements anisotropic flow coefficients. These correlations have been shown in hydrodynamic models to be sensitive to the temperature dependence of η/s (T). The measurements also provide information on the longitudinal structure of the initial state. Most current models of heavy ion collisions however assume the initial state is invariant in the longitudinal direction, an assumption that must be modified in order to accurately determine the temperature dependence of η/s. Data currently in preparation for publication will provide the guidance necessary to accurately model the initial state and extract η/s (T). J. Jia, P. Tribedy and P. Sorensen organized a RBRC workshop in January 2016 to discuss physics opportunities in studying longitudinal dynamics at RHIC. Several interesting measurements have been identified, including the event-plane de-correlation, forward-backward multiplicity correlations and net proton fluctuations. These measurements will be supplemented by data from the forward meson spectrometer (FMS) to further map out the rapidity dependence. A preliminary study with the FMS data from run 16 is ongoing.

The study of transport in the QGP extends beyond shear viscosity to bulk viscosity and even charge transport induced by the chiral anomaly in QCD through the chiral magnetic effect (CME). The three particle correlation analysis developed by the STAR group will also be applied to help determine the magnetic field dependence of the charge separation observed in heavy ion collisions. Post-doc, Tribedy, has published a paper demonstrating how the STAR ZDCs in U+U collisions can be used to disentangle magnetic field related effects from backgrounds. That analysis along with his ongoing analysis of charge separation in central and ultra-central Au+Au and U+U collisions provides strong evidence that the charge separation cannot be explained by background models pointing towards the CME as the correct explanation. The preliminary results on those analyses have been shown at the QCD workshop on chirality, vorticity and magnetic field in heavy ion collisions, UCLA 2016, and the RHIC/AGS users meeting, BNL 2016. Those works will be published in the coming year. Meanwhile the group will continue to work on related topics in preparation for the Zr+Zr and Ru+Ru collisions in 2018 which will allow STAR conclusively to pin down how much of the charge separation is related to CME.

The ability of RHIC to collide deformed nuclei, such as U+U, and asymmetric system, such as Cu+Au, provides new controls on the initial density fluctuations and overall geometry not available at the LHC. For example, ultra-central U+U collisions are expected to span much broader ranges of eccentricity distribution $P(\varepsilon_2)$ comparing to Au+Au collisions, with significant non-Gaussian tail. The $P(\varepsilon_2)$ can be probed directly by the flow probability distribution $P(v_2)$, which can be extracted via unfolding techniques developed by Jia at the LHC. Measurements of such distributions are of particular interest as they have been shown to strongly constrain models of initial conditions at LHC. Similar measurements at RHIC will help us to distinguish between models with different multi-particle production mechanisms at lower energies. The event-plane correlation in Cu+Au collisions is particularly interesting: due to strong forward-backward asymmetry, some correlators may vary strongly with rapidity (especially those involving odd harmonics), and hence the comparison with Au+Au results may provide new insights on the nature of the longitudinal fluctuations. Jia will continue analyses along this direction in 2017.

The group will also maintain its leadership role in the Beam Energy Scan program at RHIC. Tribedy and Sorensen will finalize a publication of three-particle correlations from the Beam Energy Scan data promising to provide the input necessary to constrain models needed to extract useful conclusions from the BES-II data. These analyses will be greatly improved by the increased acceptance of the STAR detector with the iTPC upgrade. The group will exploit the added abilities and increased data sets to answer crucial questions about the phase diagram of nuclear matter. Tribedy is pioneering analysis methods to measure cross correlations between conserved charges. The detailed analysis of CME signatures will also be carried out during BES-II again exploiting the expanded acceptance provided by the iTPC to extend the measurements to higher rapidity so that various sources of correlations can be disentangled. Sorensen is an organizer for a four-week INT program related to the Beam Energy Scan in October 2016, an organizer for the Critical Point and Onset of Deconfinement workshop in August 2017, and on the local organizing committee for Quark Matter 2017 in Chicago.

2) Dileptons Probing Chiral Symmetry Restoration and Quarkonia for Studying In-medium Color Screening

Ultra-relativistic heavy ion collisions at RHIC provide a unique environment to study the properties of strongly interacting matter at high temperature and high energy density. Leptons and photons are penetrating probes since they are not affected by the strong interaction once produced, and hence probe the whole evolution of the collision.

In the low invariant-mass range of produced lepton pairs ($M_{ll} < 1.1$ GeV/c^2) we can study vector meson in-medium properties through their dilepton decays. Modifications of mass and width of the spectral functions observed may relate to the possibility of chiral symmetry restoration. The dilepton spectra in the intermediate mass range ($1.1 < M_{ll} < 3.0$ GeV/c^2) are directly related to thermal radiation of the QGP. However, contributions from other sources have to be measured and evaluated experimentally. One example are background pairs from correlated open heavy flavor decays. In addition, photons in the low transverse momentum range $1 < p_T < 4$ GeV/c are used to study thermal radiation from QGP and hadronic gas. In the high-mass region ($M_{ll} > 3.0$ GeV/c^2), J/ψ, ϒ, and their excited states are used to study the color screening features of the QGP.

The BNL team (Lijuan Ruan with two post-docs Ronrong Ma, and Takahito Todoroki, five students Te-Chuan Huang, Zhen Liu, Xinjie Huang, Qian Yang, Shuai Yang, and two former students Chi Yang, and Wangmei Zha) led the efforts on low and intermediate dileptons, e-μ correlations, thermal photons, J/ψ, and ϒ production.

The detailed work for the post-docs and students is listed below:

Rongrong Ma joined our group as a post-doc in January 2014 and is a Goldhaber Fellow since June 2014. He worked on the $J/\psi \rightarrow \mu^+\mu^-$ nuclear modification factor analysis. First results with 30% of the full run 14 data from the Muon Telescope Detector in 200 GeV Au+Au collisions were obtained and presented at Quark Matter 2015 by Ma. The updated results with full run 14 statistics were presented at SQM2016 for the first time by Takahito Todoroki. In addition, he also worked on J/ψ through dimuon decays in 500 GeV *p+p* collisions. He initiated the event activity study, which was presented at Hard Probes 2015 for the first time. He, together with Te-Chuan Huang, worked on the $J/\psi \rightarrow \mu^+\mu^-$ transverse momentum spectra in 500 GeV *p+p* collisions that were shown at SQM2016 for the first time.

Takahito Todoroki joined our group as a post-doc in February 2015, he worked on $J/\psi \rightarrow \mu^+\mu^-$ - v_2 analysis. The first v_2 results were shown by Ma at Quark Matter 2015. The updated results with full run 14 statistics were presented by Todoroki at SQM2016. In addition, he studied the MTD trigger efficiency and matching efficiency comprehensively, which are important for spectrum-type analysis.

Xinjie Huang joined our group as a Ph.D. student in January 2014, he worked on $\Upsilon \rightarrow \mu^+\mu^-$ analysis. He observed the Υ signals and his first results were included in Ma's Quark Matter 2015 presentation. The updated results with full run 14 statistics were shown at SQM2016 by Todoroki.

QianYang joined our group as a Ph.D. student in March 2014, he worked on $J/\psi \rightarrow$ e+ e- in 500 GeV *p+p* collisions obtained the invariant cross section in the transverse momentum range 4-20 GeV/*c*. He also obtained the results of J/ψ production versus event activity. His results were presented by Ma at hard probes 2015 and were also presented by other STAR Collaborators at Quark Matter 2015. He is now in the process of finalizing the event-activity study.

Shuai Yang joined our group as a Ph.D. student in September 2012, he worked on e-muon correlation and dielectron continuum in U+U collisions. Preliminary results were obtained and the first U+U dielectron results were presented by Shuai Yang at Quark Matter 2015. In addition, he observed a very significant enhancement compared to the known hadronic sources and hot, dense medium effect in the very low p_T region ($p_T < 200$ MeV/c) for the dielectron pair in peripheral (40-80%) U+U collisions at 193 GeV. We plan to present the results at Quark Matter 2017. Shuai Yang graduated in June 2016 at the University of Science and Technology of China (USTC) and is at BNL as a visiting scholar.

Zhen Liu joined our group as a Ph.D student from November 2015, she is working on the di-hadron correlation using the dimuon triggered data sample. She plans to explore the jet-related analysis further in the next year.

Chi Yang (USTC): a former Ph.D. student from August 2011 to April 2014, worked on direct virtual photon production in Au+Au collisions at 200 GeV, he graduated in May 2014 and is now a post-doc at USTC. The direct virtual photon results were presented by Yang at Quark Matter 2014. The direct virtual photon paper based on Yang's thesis was submitted on July 2nd, 2016 to Phys. Lett. B for publication.

Wangmei Zha (USTC): a former Ph.D. student from January 2012 to April 2014, and worked on J/ψ production in Au+Au collisions at 39, 62,4 and 200 GeV, graduated in June 2014 and is now a post-doc at USTC. The low-energy J/ψ results were presented by Zha at Quark Matter 2014. The paper based on Zha's thesis has passed the GPC review and now in the stage of Collaboration review. We expect to submit this paper to Phys. Lett. B in August 2016. In addition, during his short visit to BNL in 2016, he also observed a very significant enhancement compared to the expected hot, dense medium effect in the very low p_T region (p_T < 200 MeV/c) for the J/ψ in peripheral (40-80%) Au+Au collisions at 200 GeV. The results were presented by Zha for the first time at SQM2016.

Ruan also served as the organizer of the RHIC and AGS Users Open Forum Meeting in October 2015 in Santa Fe, New Mexico, co-organizer for the annual RHIC and AGS Users Meeting 2016, BNL, and co-organizer for the Hot Quark 2016 conference in South Padre Island, Texas from September 11-17, 2016. In addition, Ruan is one of the IAC members for the Hard Probes 2016 conference.

Publications by the team are listed below:

1. "Direct virtual photon production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV", L. Adamczyk et al. (STAR Collaboration), submitted to Phys. Lett. B, (Chi Yang and Lijuan Ruan are two of the principal authors).

2. "J/ψ production in Au+Au collisions at $\sqrt{s_{NN}}$ = 39, 62.4 and 200 GeV", L Adamczyk et al. (STAR Collaboration), submitted to Phys. Lett. B, (Wangmei Zha and Lijuan Ruan are two of the principal authors).

3. "Muon Identification with Muon Telescope Detector at the STAR Experiment", T.C. Huang, R. Ma, B. Huang, X. Huang, L. Ruan, T. Todoroki, Z. Xu, C. Yang, S. Yang, Q. Yang, Y. Yang, W. Zha, submitted to NIMA, arXiv: 1601.02910.

4. "Measurement of jet quenching with semi-inclusive hadron-jet distributions in central Pb-Pb collisions at $\sqrt{s_{NN}}$ == 2.76 TeV", ALICE Collaboration, JHEP 09 (2015) 170, (Rongrong Ma being one of the principal authors).

5. "Systematic study of the experimental measurements on J/ψ production and kinematic distribution in *p+p* collisions at different energies", Wangmei Zha, Bingchu Huang, Rongrong Ma, Lijuan Ruan, Zebo Tang, Zhangbu Xu, Chi Yang, Qian Yang, and Shuai Yang, Phys. Rev. C93 (2016) no.2, 024919.

Research plan for FY2017:

Ruan and her team will continue to work on dilepton and quarkonium physics. We expect the direct virtual photon paper and low p_T J/ψ production paper at BES energies to be published. The dielectrons at 27, 39, and 62 will be finalized and submitted for publication. We expect to finalize the very low-p_T dielectron and J/ψ analysis in peripheral Au+Au and U+U collisions.

In addition, we will work on the following for the MTD:

- Finalize J/ψ $\rightarrow \mu^+\mu^-$ cross section and event activity measurements in 500 GeV *p+p* collisions, and write a paper on cross section and event activity towards publication. In the paper, the results using dielectron decay channels will also be included. The goal is to submit the paper to PRC or PLB.

- Finalize, J/ψ $\rightarrow \mu^+\mu^-$ R_{AA} and v_2 measurements in 200 GeV Au+Au collisions and write a paper for publication. The goal is to submit the paper to PLB.

- Finalize different ϒ states ratio measurements in 200 GeV Au+Au collisions and write a paper for publication. The goal is to submit the paper to PRL.

- We implemented HLT to select interesting quarkonium events in run 16. We plan to finish the calibration, have the data produced, and show the results from the combined data sets of runs 14 and 16 to Quark Matter 2017.

- With run 15 *p+p, p*+Au production on-going, we plan to show *p+p, p*+Au results at Quark Matter 2017.

- Hire a new post-doc who will focus on the measurements of dimuon continuum and e-muon correlation.

- To explore the jet-related analysis further in the next year with dimuon data sample.

3) Observation of Charge Asymmetry Dependency of Pion Elliptic Flow and Possible Chiral Magnetic Wave in Heavy Ion Collisions

In relativistic heavy ion collisions, energetic spectator protons produce an extremely strong magnetic field. The interplay between the magnetic field and quark-gluon matter can be characterized by two phenomena: the chiral magnetic effect (CME) and the chiral separation effect (CSE). Theoretical studies argue the in heavy ion collisions CME and CSE can form a collective excitation, called the chiral magnetic wave (CMW). If it exists, the CMW can lead to a learning increase of the elliptic flow between positive and negative pions as a function of charge asymmetry. We measured this difference in Au + Au collisions from 200 GeV to 7.7 GeV. The resulting paper has been published by Phys. Rev. Letter, highlighted as Editor's recommendation. After the publication, it is argued by Hatta et al (Nucl. Phys. A 947 155 (2016)) that "STAR results can be understood within the standard viscous hydrodynamics without invoking the CMW", and they propose to testing this idea with kaons: the slope that quantify the linear increase of the splitting between pion- and pion+ elliptic flow with the increasing of charge asymmetry would be negative in contrast to the pion case, assuming their mechanism is correct. We are currently working on the result for kaons. Our preliminary result clearly shows that the kaon slope has the same trend and sign as that of the pions, indicating that it is not possible to be explained by the standard viscous hydrodynamics without invoking the CMW. The result has been initially presented at the SQM conference and, with better significance, at the following conferences: QCD workshop on chirality, vorticity and magnetic field in heavy ion collisions, UCLA 2016, and the RHIC/AGS Users Meeting, BNL 2016. We are working now on finalizing the systematics and summarizing the result in a comprehensive publication. We are also working on the CMW in U+U collisions where we have observed similar result for both, pions and kaons. In parallel, we are investigating the locality of the CMW effect by changing the separation gap between particles used to calculate the flow difference, and particles used to calculate the charge asymmetry. The result may be merged in the paper in preparation aforementioned.

Aihong Tang, along with Gang Wang from UCLA, are also investigating the possibility of studying circular-polarization differences w.r.t the reaction plane in connection with the magnetic effects, for both photons and vector mesons. The idea is that the strong magnetic field will cause more right handed particles than left handed particles in the hemisphere above the RP, and vice versa in the lower hemisphere. We have laid out a procedure to identify and quantify such effects and will submit it for publication. Independently, we are also working on this subject with experimental data.

4) Physics with Nuclear Beams at a Future Electron-Ion-Collider

The 2015 Long Range Plan for Nuclear Science in the US recommends a high-energy high-luminosity polarized EIC as the highest priority for new facility construction. The EIC will, for the first time, precisely image gluons in nucleons and nuclei. This science will be made possible by the EIC's unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.

Studies at the EIC will provide unprecedented access to a regime in which the structure of nuclei is dominated by the dynamic of gluons. Specifically, the EIC will allow us to map the low-x regions of the nuclear wave function with e+A collisions with the potential to discover a new form of gluon matter. This can be achieved with unparalleled precision well beyond those available at existing facilities worldwide. This is key topic that is being addressed by members of STAR's heavy ion group. The group was and is involved in (i) evaluating the physics opportunities in e+A collisions at an EIC as well as (ii) conceptual studies for a collider detector that is able to capture the rich physics program of such a unique facility. Both required detailed physics simulations and close collaboration with ongoing accelerator design efforts and ongoing theoretical work on this subject.

In 2015 the STAR members of EIC Science Task force (Matt Lamont, J.H. Lee, and Thomas Ullrich) have successfully supported an international effort to develop the science case for this facility, producing software required to generate rigorous, quantitative simulations of physics processes for QCD phenomena in the EIC regime and the machine and detector requirements for key measurements. This effort was continued in 2016 by Lee and Ullrich after the departure of Lamont. A search for a new postdoc is underway. This position will be financed through BNL program development funds. The postdoc will be part of the STAR BNL group.

A partial list of critical accomplishments by members of the STAR group follows:

Making the Physics Case for the Long Range Plan – The EIC White Paper

This White Paper presents the science case of an Electron-Ion Collider (EIC), focused on the structure and interactions of gluon-dominated matter, with the intent to articulate it to the broader nuclear science community. It was commissioned as a follow-up to the 2007 NSAC Long Range plan. The studies featured in *e*+A part of the White Paper were almost all carried by the EIC Task Force at BNL, which consist by members of the STAR group. Although the first version of the White Paper was published in 2012 it underwent a substantial update in 2015 shortly before the Long Range Plan. Especially parts of the *e*+A chapter were substantially revised. The studies on which these updates are based on by members of this group are:

- Dihadron Correlations in *e*+A Collisions (Lee and Zheng a student from CCNU)
- Structure Function in *e*+A Collisions (Lamont and Ullrich)
- Exclusive and Inclusive Diffraction (Toll and Ullrich)

These were described in more detail in the previous report. Ullrich in collaboration with Yuri Kovchegov (Ohio) wrote the original as well as the updated *e+A* section of the White Paper. All members of the STAR group involved in the EIC provided critical input into the White Paper and the Long Range Plan effort. The success of the EIC in the NSAC Long Range plan is, to no small part, founded on the work of STAR members, through their simulation studies, their publications, and the many talks, colloquia, and seminars given in and outside of the US.

The EIC Detector R&D Program

In January 2011 Brookhaven National Laboratory, in association with Jefferson Lab and the DOE Office of Nuclear Physics, announced a generic detector R&D program to address the scientific requirements for measurements at a future Electron Ion Collider (EIC). The primary goals of this program are to develop detector concepts and technologies that have particular importance for experiments in an EIC environment, and to help ensure that the techniques and resources for implementing these technologies are well established within the EIC user community. This program is supported through R&D funds provided to BNL by the DOE Office of Nuclear Physics and is funded at an annual level of $1.0M - $1.5M, subject to availability of funds from DOE NP. The program is administered by the BNL Physics Department. Since 2014 Thomas Ullrich is the managing and organizing the program. Funded proposals are selected on the basis of peer review by a standing EIC Detector Advisory Committee consisting of internationally recognized experts in detector technology and collider physics. This committee meets approximately twice per year, to hear and evaluate new proposals, and to monitor progress of ongoing projects. The next meeting takes place at ANL with a record participation of 17 groups that put forward new proposals.

***Dijet production and correlation in e*+A**

Transverse momentum dependent (TMD) factorization in deep inelastic scattering in *e*+A predicts a distribution for linearly polarized gluons in an unpolarized target. In the Color Glass

Model this is reflected in cos2φ asymmetries (v_2) in dijet production and in other processes (Phys.Rev.Lett. 115 (2015), 252301). To date little is known about the magnitude of these functions in the small-x regime of high energies. In conventional pQCD no azimuthal asymmetries are expected making these dijet correlations a novel probe of gluon saturation. Together with the authors of the underlying theoretical model, A. Dumitru (CYNU), and V. Skokov (RIKEN/BNL), Ullrich started to conduct detailed study of dijets in *e*+A collision to test the feasibility of these measurement in a realistic experiment. The partons carrying the signal correlations are produced by an MC event generator written by V. Skokov. Ullrich then propagates these partons through Pythia for parton showering and hadron formation, which are then fragmented into particles and filtered applying detector acceptance, cuts, and smearing. On the final data jet finding is performed and the cos2φ asymmetries of dijets studied. In parallel studies with conventional MC generators (Pythia) are generated to compare predicted novel physics outcome with current standard distributions. The results are very encouraging showing that the cos2φ asymmetries present on the parton level is well measurable experimentally and that the energies of an eRHIC are well matched to investigate this effect. Studies also showed that the effect is not present in data from conventional physics generators. Results of this study are expected to be published in the near future.

Accessing Gluon Sivers Distribution in polarized e+p

Studying the largely unexplored gluon Sivers function (GSF) is important to obtain a complete picture of the 2D+1 momentum structure of the proton. It has been proposed that the GSF can be studied through the dihadron single spin asymmetry (SSA) with a future high energy, high luminosity EIC. We started a detailed study on the feasibility of measuring the dihadron SSA arising from the GSF with the back-to-back charged hadrons, K^+K^- and DDbar pair. It has been shown that DDbar pair is a clean probe for the study while measuring it will be statistically challenging. We've explored feasibilities of measuring the GSF with other gluon probing channels - unidentified dihadron correlations and also with K^+K^- pair. (Lee collaboration with Elke Aschenauer and Liang Zheng (CCNU) and Bowen Xiao (CCNU))

Refining detector requirements for e+A in the shadowing/saturation regime

We are working on refining the detector requirements for *e*+A Collisions in the Nuclear Shadowing/Saturation Regime. It has been propose to upgrade the *e*+A DIS event generator DPMJetHybrid (developed by Aschenauer, Lee, and Zheng) to include some key nuclear shadowing / parton saturation effects that are currently missing in the suite of *e*+A event generators available for physics simulations. These event generators have been essential in establishing detector requirements for various physics measurements. However, the particle production model in the forward region for *e*+A needs improvement in order to clarify those requirements for measurements at an EIC. We have started increasing the flexibility of the *e*+A generator by tuning and adding intrinsic k_T and multi-nucleon k_T-recoil sharing for *e*+A collisions. This model will automatically factor in improved information as we include updated nuclear PDFs from RHIC or the LHC. In order to test and tune the model, we plan to use it to study the impact of forward detectors on two important topics in *e*+A: centrality measures and correlations between forward particles and particles from the hard scattering, extending the study performed by Elke Aschenauer, JH Lee, and Liang Zheng. (Lee in collaboration with Aschenauer, Mark Baker and Zheng (CCNU))

Studying photon structure in photoproduction

In ep collision, the interaction of electrons and protons at low virtuality is dominated by photoproduction processes with electrons scattering at small angles. At EIC, the resolved and direct processes can be well separated. We have reconstructed x_γ by tagging di-jets produced in resolved processes based on the existing Monte Carlo framework. The unpolarized photon PDFs can be extracted by measuring the di-jets cross section. In the next step, we will continue working the polarized photon PDFs, which is a critical input for $\gamma\gamma$ ILC option. (Lee collaboration with Elke Aschenauer, Xiaoxuan Chu, and Marco Stratmann (Tübingen)).

5) Heavy Flavor Tracker (HFT) and Related Physics

Flemming Videbaek and Long Zhou a student from USTC, are involved in the HFT project and research with this detector. The coordination for the HFT detector system is done by a smaller management team lead by Videbaek, responsible for operations, calibrations and any needed software development for the detector. The detector was fully operational for run 16 and took 2B Minimum Bias Au+Au events within a narrow vertex. Videbaek is also active in the leadership of the STAR HFT software group. In particular he was involved in many aspects of the Q&A process of detector performance, on data quality, and alignment, which are all critical to achieve high precision data. The analysis of data taking in run 14 has yielded several results in heavy flavor physics that were presented at QM 2015.

Long, under the supervision of Videbaek, has been involved in the online and offline software for the SSD, and is working to understand the detector response, and to optimize the software for analysis. As part of his interest in HF physics he has worked on the systematics of pp from 200 to 500 GeV to get a better handle on the underlying D0 spectra at high p_T. Long is working on DS analysis of Au+Au data from run 14 to present a poster at Quark Matter 2015 and a parallel talk at SQM 2016 in Berkeley. Videbaek worked as co-advisor for Amilkar Quintero (Kent State University). His thesis work was a study of spectra and Rcp for D0 in Au+Au from run 14, and has also developed TVMA methods for signal enhancement. Quintero received his Ph.D. degree in May 2016.

Activities with BRAHMS

Three members of the STAR group (Debbe, Lee and Videbaek) have a small effort in editing and bringing to publication the last results from the BRAHMS experiment. Drafts on *p+p* results at 62.4 and 200 GeV have been prepared. Key results are comparisons with transverse and rapidity distributions of identified charged hadrons with model calculations, including Next to Leading Log (NLL), PYTHIA and EPOS. The paper is being revised after comments from the collaboration. A second paper on Cu+Cu heavy ion collisions at 200 focusing on mid-rapidity transverse spectra at mid and forward rapidity has been submitted and accepted for publication in PRC.

"Rapidity and centrality dependence of particle production for identified hadrons in Cu+Cu collisions at $\sqrt{s_{NN}}$) = 200 GeV", BRAHMS Collaboration, Phys. Rev. C **94** (2016) 019407.

6) Operation of Muon Telescope Detector and Related Physics

Lijuan Ruan, the project manager of the Muon Telescope Detector (MTD), worked with Post-docs Rongrong Ma and Takahito Todoroki and Ph.D. students Xinjie Huang, Qian Yang, Shuai Yang on the MTD. In run 16, STAR requested CAD to reduce the luminosity and provide a modest luminosity profile as a function of time in each fill, in order to complete the physics goals with the Heavy Flavor Tracker. In addition, a 10-week run was approved for 200 GeV Au+Au instead of a 13-week run requested by STAR. Nine nb^{-1} effective luminosity was achieved by the end of 200 GeV Au+Au run in run 16, which is 1 nb^{-1} less than what we requested.

The team has been leading in every aspect of the MTD software and hardware efforts. For the software, the team did the MTD calibrations using cosmic ray data and prepared the code for all of the integration efforts. The team established the efficiency correction procedure with simulations and cosmic ray data samples. The procedure has been successfully applied to the data of 500 GeV p+p collisions in run 13 and 200 GeV Au+Au collisions in run 14. For the hardware, the team provided the major workforce for runs 14, 15, and 16 as on-call experts during data taking. In addition, the team was in charge of the trigger commissioning efforts for the MTD system.

The detailed work for the post-docs and students is listed below:

Rongrong Ma is the software coordinator for the MTD system. He has worked on almost all the software integration tasks. In addition, he was one of the on-call MTD/TOF experts for runs 15 and 16. In run 16, he worked with the high-level trigger group to implement a high-level-trigger to select interesting quarkonium events. We plan to finish the calibration, have the small quarkonium stream data sample produced, and show the results from the combined data sets of runs 14 and 16 to Quark Matter 2017.

Takahito Todoroki worked on the offline MTD trigger efficiency and matching and response efficiency. He was one of on-call MTD/TOF experts for run 16.

Shuai Yang (USTC) worked on the MTD trigger commissioning for runs 13-16. He optimized the offline particle identification cuts with the MTD to maximize the significance of quarkonium. In addition, he was one of the on-call MTD/TOF experts for runs 14 -16.

Qian Yang (USTC) worked on the MTD matching algorithm optimization and helped VPD and MTD trigger commissioning. In addition, he was one of the on-call MTD/TOF experts for runs 15 and 16.

Xinjie Huang (Tsinghua University) worked on the MTD calibration software and did the MTD calibration for runs 13 - 15. In addition, he was one of the on-call MTD/TOF experts for runs 14 and 15.

Plan for Run 17:

Will make sure the run 17 is smooth for 500 GeV *p+p* collisions. This would be the first time that the full system takes data for 500 GeV *p+p* collisions. The goal of this data set is to obtain the different Upsilon states ratio in this system since a higher energy is beneficial for Upsilon measurements due to a higher luminosity and a higher production cross section. We will continue to lead the efforts as the on-call experts, and MTD trigger commissioning. On the software, we will continue to lead the efforts on the calibration of run 16 data, integration, and MTD data analysis.

7) Development and Operation of the STAR High Level Trigger (HLT)

The main purpose of building the STAR HLT is to select interesting events based on criteria applied to online reconstructed events. The fast reconstruction is performed in a high performance computer farm. Because HLT can access data from all sub-detectors, it can implement far more sophisticated trigger algorithms than those implemented by low-level hardware triggers.

Aihong Tang is also working on J/ψ elliptic flow and directed flow. The previous publication is with run 10 data, and is on elliptic flow only. We are extending the analysis for directed flow, with both run 10 and 11's data.

We published a letter in Nature on the measurement of interaction between two antiprotons. So far the large body of knowledge of nuclear force was derived from studies made on nucleons or nuclei, although antinuclear up to antihelium-4 have been discovered and their masses measured, we have no direct knowledge of nuclear force between anti nucleons. Tang, with (Zhengqiao Zhang, SINAP, student) under his guidance, led the effort of measuring for the first time the interaction between antiprotons, and reported the corresponding scattering length (f^0) and effective range (d^0). Since two interacting antiprotons constitutes one of the simplest systems of antinucleons, this result provides a fundamental ingredient for understanding the structure of more complex antinuclear and their properties. Since the publication in Nature, our work has been covered by major media around the world, and generated lots of public interest towards the science at RHIC.

The group is the leading contributor in developing and operating the HLT. This year we have extended the online HLT farm with 18 more high performance servers. We have integrated the Muon Tracker Detector (MTD) information into the HLT and implemented HLT based triggers into the MTD program. In run 16 the HLT also helped STAR on commissioning, and CAD on beam optimization, by providing the real time vertex distribution. We are exploring tracking with Celluar Automaton on STAR's HFT hits, as well as the associated online calibrations for the HFT. For that purpose, we had two successful, dedicated tracking workshops between CBM and STAR experts in the past year.

In order to assess and improve STAR’s tracking performance, STAR formed a tracking focus group in 2015, led by A. Tang and S. Margetis (Kent State University). Other major contributors from the BNL group are Y. Fisyak, H. Ke and I. Chakaberia. We have re-evaluated the StiCA tracker and proved that it enhances the efficiency for the W signal by 15-20%, and D^0 signal by

~20%. The increase of efficiency on the W signal had considerable impact on the STAR Beam Use Request for 2017. This tracker has been integrated into STAR standard library and is ready to be used in production. In terms of performance on timing, we have identified a compilation issue which when fixed, successfully reduces STAR's offline reconstruction time by a factor of ~2. The tracking focus group also tried to alleviate the online bandwidth problem by reducing the event size, with a tighter cut on the threshold of the TPC readout. The tracking focus group will continue to explore ideas for improvement on tracking and data reconstruction. Future direction may include processing data with the online HLT farm during data taking, improvement on tracking in forward region, CA tracking with HFT hits, KFParticle construction and improvements on vertex finding etc.

8) Forward Upgrade for STAR

STAR has started to study the feasibility of a forward detector upgrade including an Event Plane Detector (EPD), a Forward Calorimeter System (FCS) and a Forward Meson Spectrometer (FMS) for heavy ion physics in the years after the BESII in parallel with sPHENIX (2021-2022) running. Jiangyong Jia and Paul Sorensen lead this effort. They have identified several measurements based on a large class of new correlation observables that can be uniquely measured by STAR at RHIC, which will help further elucidate the space-time picture of the QGP evolution in both the transverse and longitudinal directions.

a) Event plane decorrelation and flow factorization breaking in pseudo-rapidity, which provide important constraints on the initial geometry and the temperature dependence of η/s.

b) FB multiplicity correlation, especially the FB net-baryon correlation, utilizing the excellent PID capability of the upcoming iTPC upgrade, which allows understanding of the nuclear stopping and transport mechanism of net-protons.

c) Correlation of event-plane of different orders and $v_n(p_T)$ measurement in forward rapidity, which will provide important insights on disentangling the linear and non-linear response of the medium to the initial state fluctuations, and the temperature dependence of the γ/s. Simulation efforts have begun in STAR to quantify the capability of STAR upgrades for these measurements. An RBRC workshop organized by members of our group has attracted community interests from theorists and experimentalists to further such studies and strengthen the physics case.

9) Calorimetry

The focus remained on developing forward instrumentation in 2015-2016, specifically on a forward calorimeter (FCal) with good response to both incident electromagnetic and hadronic particles. In this time period, public reports of our 2014 collision data obtained with a pixelized FCal, and the test beam data from Fermilab (T1064) were presented at the Division of Nuclear Physics meeting in October, 2015 by a student (Prashanth Shanmugathan, of Kent State), who is presently a postdoctoral research associate at Lehigh University. Reports were also made to an electron-ion collider subgroup of STAR.

There were two aspects to new efforts in the 2015-2016 period: one on hardware, to address "environmental" issues, and one on analysis, to establish as best as possible the full scope of possibilities that forward instrumentation can provide.

There are several "environmental" issues that must be dealt with when trying to improve the forward instrumentation at STAR, specifically by the addition of an existing FCal that had been in place at IP2. Probably the most important issue is magnetic field effects on photomultiplier tubes (PMT). Forward physics at STAR is made possible by the ~2-m hole in the east and west poletips. These holes also allow magnetic flux from the STAR solenoid to escape. The most natural geometry for forward calorimetry results in magnetic fields along the symmetry axis of PMT, when they are used as FCal photosensors. In the run 14 test, we measured 150 Gauss primarily in the z direction across essentially the entire $(60\text{cm})^2$ area of the test calorimeter. This field was shielded by extending a soft-iron shell around the calorimeter in the z direction. The shield proved to be effective for ~2/3 of the calorimeter, although the shield could not be sufficiently extended for the bottom ~1/3 of the test FCal. Making a shell to guide magnetic fields around a larger calorimeter is difficult. In 2016, we designed and fabricated a pixelized focusing light guide that used inexpensive Fresnel lenses to allow focusing of the scintillation light from FCal pixels into PMT that were recessed by more than twice their diameter into 0.05-cm thick mu-metal cylinders. This solution can work for modular FCal, as had been in place at IP2, when the modules are rotated by small angles with respect to the line of the colliding beams. Tests were conducted in run 16 on the east side of the STAR solenoid. The shielding was demonstrated completely effective in tests of a PMT response to a pulsed blue light emitting diode (LED). No loss of PMT resolution nor gain was observed with the STAR solenoid at full field or at any point in a RHIC ramp to full energy. Field effects on FCal PMT have been observed from DX fringe field effects in the past. Direct measurement of the fringe field from the STAR solenoid was made on the east side, and found to be only 20 Gauss, primarily in the z direction. The east/west asymmetry illustrates the role of iron surrounding the solenoid, including the endcap electromagnetic calorimeter PMT boxes on the west poletip, the support stand for the forward meson spectrometer and the poletip extraction mechanism. The material complexity is such that realistic calculations are not possible.

A second environmental issue is radiation, associated with each beam singly and the collisions between the two beams. RHIC operations now make lead-glass based calorimetry difficult, because of the build-up of color trapping centers that change glass transparency with time. We have demonstrated that the test FCal cells are stable with time, as expected by the orders of magnitude larger dose before radiation damage effects set in. Tests were conducted in run 16 with 2×2 arrays of Hamamatsu S12572-025 multi-pixel photon counters (MPPC). These photosensors are attractive because they do not respond to magnetic fields and are relatively inexpensive. However, it is known that their leakage current increases with time when they are operated during low-energy neutron irradiation, at fluxes which are typical when RHIC is operating. The tests done this year consisted of comparison of PMT and MPPC response to a pulsed blue LED during 28 days of RHIC operation. Three sets of thermoluminescence detectors recorded the dose delivered to the detectors. Data consisted of MPPC leakage current measurements and oscilloscope traces from the PMT and MPPC recorded every 10 minutes. Full analysis of this data is underway, with preliminary results showing that MPPC underwent a

25% gain reduction as their leakage current increased with time. This is not suitable for FCal operation.

A third environmental issue is electronic noise. Tests conducted in 2014, using 324 of the 1264 channels of readout implemented for the forward meson spectrometer (FMS), revealed several noise sources, some of which were fixed during the tests by replacing clock receiver boards. The need for cosmic-ray muon data from run 14 test FCal resulted in attempts at operating the trigger at low thresholds on the ADC sum. This trigger had proven quite effective for cosmic-ray muons during the brief effort with forward calorimetry at IP2. Noise in the FMS electronics required special workarounds (such as the introduction of large deadtimes to prevent noise from the VME data transfers from retriggering the system) to allow acquisition of cosmic-ray data. Offline analysis of run 14 data revealed other noise patterns, not all of which are understood. In any case, tests conducted in run 16 used standalone electronics for a 54-pixel test FCal. The data acquisition system had been developed for the IP2 effort, and had been previously used during test beam (T1064) at FermiLab. As with those two previous efforts, the standalone electronics was noise free in the run 16 tests providing confidence that there is no intrinsic issue with the flash ADC or digital trigger boards.

In addition to targeted tests of MPPC arrays and magnetic shielding, a 54-pixel test FCal was constructed in 2016, with involvement of two graduate students from Lehigh University. Half of the pixels used conventional acrylic light guides. The other 27 pixels used a focusing light guide, using Fresnel lenses. Of those 27, scintillation light from nine pixels was focused onto bundles of clear optical fiber for light transport to MPPC arrays. The other 18 pixels used Fresnel lenses to focus light onto PMT that were recessed into mu-metal cylinders. Direct comparison between these two sets of pixels can determine the relative light collection efficiency. After a thorough safety review, this device and the standalone data acquisition system were installed in the east tunnel and wide angle hall, respectively, to acquire data from Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. A total of 80M triggers were recorded. Analysis of that data is underway, and will be primarily done by the group at Lehigh University. Initial reports to the jet correlations working group will be made by the Lehigh group at the August 2016 STAR collaboration meeting. Full reports of findings from run 16 FCal tests will be presented.

Analysis efforts were interspersed with hardware work throughout the past year. Forward inclusive jet and dijet measurements that have been previously reported were carefully compared to tunes of event generators (PYTHIA) that were developed for the LHC. A tune reported by LHC-Atlas within the past year was found to describe both inclusive forward jet and dijet production in *p+p* collisions at $\sqrt{s}$=510 GeV. This was reported at the Santa Fe workshop on jets in January 2016. Such data driven tunes are required before realistic simulations for rare processes such as Drell Yan production are meaningful. Event generator tunes that work at midrapidity for RHIC collision energies do not describe forward jet and dijet data.

Given the situation that an FCal must have broad appeal for it to be approved by the diverse STAR community, investigations into the utility of forward jets in Cu+Au collisions at $\sqrt{s_{NN}}$=200 GeV were conducted. A small sample of collision data had been collected at IP2 before the effort there was terminated. Although it had been briefly examined soon after its acquisition, a more thorough investigation was not initially possible because of the time required to completely analyze and publish the inclusive jet data from polarized proton collisions. This was remedied within the past six months, by applying the jet reconstruction coding developed for *p+p* collisions to semi-peripheral Cu+Au collisions. Despite the bias that forward detectors would be dominated by underlying event contributions from a heavy-ion collision, inclusive jets from semi-peripheral Cu+Au collisions bear strong resemblance to jets from *p+p* collisions. An interesting aspect is that the jets have energies which exceed Feynman-x values of unity, when considering they are produced individual nucleon-nucleon collisions from the Cu+Au colliding ions and do not undergo large final-state interaction effects. This was reported at the Santa Fe workshop in January 2016.

The analysis coding developed for dijets produced in *p+p* collisions was then applied to the Cu+Au data. It was already known that the *p+p* data resulted in a structure with statistical significance of 3.1σ in dijet mass which we attributed to $\chi_{2b} \rightarrow 2g$ in written reports. In our refereed publication, we reported a structure with statistical significance of 3.5σ in 3-jet mass which we attributed to $\Upsilon(1S) \rightarrow 3g$, after demonstrating the structure was compatible with $\Upsilon(1S)$ from simulations of its decay to three gluons, with events then run through our GEANT and our event reconstructions. Our publication noted this primarily as a direct check from data of our jet energy scale. However, the dynamics that give rise to this could also be of great interest, because it could be related to the phenomenon of long-range rapidity correlations similar to those seen at the LHC. These hints from very limited data are only present when we select on particle multiplicity at $\Delta\eta \sim 7$ units from the dijet. For semiperipheral Cu+Au, there is adequate data to show that azimuthal correlations with particle multiplicity at $\Delta\eta \sim 7$ units from the dijet show near-side ($\Delta\varphi \sim 0$) and away-side ($\Delta\varphi \sim \pi$) peaks sitting atop background. These peaks are most evident when the dijet energies exceed Feynman-x scaling limits. Selecting events on the $\Delta\varphi \sim \pi$ azimuthal correlation results in a smooth dijet mass distribution. Selecting events on the $\Delta\varphi \sim 0$ azimuthal correlation results in a narrow peak in dijet mass that sits on top of a smooth dijet mass background which resembles the mass distribution for $\Delta\varphi \sim \pi$ events. The narrow peak in mass from dijets produced in semi-peripheral Cu+Au collisions is at 20.5 GeV/c^2 and has statistical significance of 5.1σ. Discussions of these results are just beginning. Systematic studies are still underway. We anticipate a report of our efforts could be of interest to many.

In addition, a draft manuscript describing our run 14 FCal tests at STAR was written. The emphasis was on ^{3}He+Au collision data at $\sqrt{s_{NN}}$=200 GeV, where complexities from calorimeter occupancies are less severe than for the Au+Au data that was also acquired. Given that the run 16 tests were done with Au+Au collisions, the run 14 Au+Au data has been revisited so that a good reference from the run 16 tests is made available to the Lehigh group. The plan is to complete the manuscript with the addition of these Au+Au results.

We have prepared a proposal to install an FCal at STAR in 2017, which reuses most of the equipment that was in place at IP2 for our forward jet measurements, and hence is a very low cost solution for new capability. New STAR groups have joined this effort with both graduate students and postdocs. The reality of their commitment was made clear by two students being resident at Brookhaven during the culmination of the run 16 FCal tests. Wary of the many ongoing efforts prior to the resumption of RHIC operations in 2017, our proposal requires only strategic help from the Brookhaven technical staff. As was done for the 2016 tests, most of what we propose we will implement from our own technical efforts.

Invited Talks Presented by Group Members in the past year:

1. J. Jia, “Forward-Backward Multiplicity Correlations in PbPb, pPb and pp Collisions from ATLAS", XXVth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (QM2015), Kobe, Japan, September 27 - October 3, 2015.

2. R. Ma, “Preliminary Analysis of Quarkonium Production in the Dimuon Channel”, XXVth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (QM2015), Kobe, Japan, September 27 - October 3, 2015.

3. R. Ma, “Analysis of J/psi Production vs. Event Activity and Cross Section in 500 GeV”, XXVth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (QM2015), Kobe, Japan, September 27 - October 3, 2015.

4. J. Jia, “What do Recent ATLAS Measurements Tell us about the Dynamics and the Properties of Quark-Gluon Plasma?", LHC Seminar, CERN, Geneva, Switzerland, October 13, 2015.

5. F. Videbaek, “The STAR iTPC Upgrade for BES-II”, DNP 2015: APS Division of Nuclear Physic, Santa Fe, New Mexico, October 28-31, 2015.

6. J. Jia, “Azimuthal and Longitudinal Correlations in pp Collisions", Minimum Bias and Underlying Event Working Group, CERN, Geneva, Switzerland, November 19, 2015.

7. L. Ruan, “Electron-Positron Tomography of Hot, Dense Medium Created in Heavy Ion Collisions”, Nuclear Particle Astrophysics Seminar, Yale University, New Haven, Connecticut, November 20, 2015.

8. A. Tang, Measurement of Interaction between Antiprotons”, Seminar, Brookhaven National Laboratory, Upton, New York, November 19, 2015.

9. P. Tribedy, “Multi-Particle Production in Small Systems from CGC”, 7th International Workshop on Multiple Partonic Interactions at the LHC, ICTP, Trieste, Italy, November 26, 2015.

10. A. Tang, “Experimental Study of Chiral and Matter-Antimatter Symmetries RHIC”, Colloquium, Brookhaven National Laboratory, Upton, New York, December 15, 2015.

11. T. Ullrich, "Structure Functions and Nuclear PDFs in eA Collisions", EIC User Group Meeting, Lawrence Berkeley National Laboratory, Berkeley, California, January 6-9, 2016.

12. A. Tang, “Experimental Study of Chiral and Matter-Antimatter Symmetries at RHIC”, Brookhaven Science Council, Brookhaven National Laboratory, Upton, New York, January 12, 2016.

13. L. Bland, “Cross Sections and Spin Observables for Forward Jet Production”, Workshop of Jets and Heavy Flavor, Santa Fe, New Mexico, January 11-13, 2016.

14. J. Jia, “Some Thoughts on the Longitudinal Correlations", RBRC Workshop on Opportunities for Exploring Longitudinal Dynamics in Heavy Ion Collisions at RHIC, Brookhaven National Laboratory, Upton, New York, January 20-22, 2016.

15. P. Tribedy, “Charge Sensitive Cumulants and Flow in U+U Collisions from STAR”, 2nd QCD Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collision, UCLA, February 23-26, 2016.

16. P. Sorensen, “Report on the CME Task Force”, 2nd QCD Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collision, UCLA, February 23-26, 2016.

17. J. Jia, “Longitudinal Correlation in Heavy Ion Collisions", 2nd QCD Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collision, UCLA, February 23-26, 2016.

18. P. Sorensen, “Beam Energy Dependence of the Third Harmonic of Azimuthal Correlations in Au+Au Collisions at RHIC”, Seminar, Brookhaven National Laboratory, Upton, New York, March 1, 2016.

19. F.Videbaek, “HFT Project Experience”, sPHENIX MAPS Workfest, Santa Fe, New Mexico, March 2016.

20. P. Sorensen, “Ripples from the Quark Gluon Plasma”, Brookhaven Science Council, Brookhaven National Laboratory, Upton, New York, March 8, 2016.

21. T. Ullrich, "The Glue That Binds Us Imaging Matter Below 10-15m with an Electron-Ion Collider", Colloquium, University of Texas at Houston, Houston, Texas, March 24, 2016.

22. T. Ullrich, "Studying Small-x Physics at an EIC", XXIIIrd International Workshop on Deep-Inelastic Scattering and related Subjects (DIS 2015), Dallas, Texas, April 27 - May 1, 2015.

23. Z. Xu, “STAR Highlights and RHIC BES-II Program”, Symposium, Shandong University, Shandong, China, May 3, 2016.

24. L. Bland, “Forward Particle Production at Colliders”, Seminar, University of Maryland, Collage Park, Maryland, May 4, 2016.

25. P. Sorensen, “Emergent Properties of QCD and its Phase Diagram”, QCD at Cosmic Energies VII, Chalkida, Greece, May 16-20, 2016.

26. J. Jia, “The Role of Longitudinal Correlations and Fluctuations", Initial Stages 2016, 3rd International Conference on the Initial Stages in High-Energy Nuclear Collisions, Lisbon, Portugal, May 23 - 27, 2016.

27. P. Tribedy, “Bulk Observables in Small Colliding Systems using Yang-Mills Dynamics and Lund String Fragmentation”, 3rd International Conference on the Initial Stages in High-Energy Nuclear Collisions, Instituto Superior Tecnico, Lisbon, Portugal, May 25, 2016.

28. J.H. Lee, “'Electron Ion Collider', 3rd International Conference on the Initial Stages in High-Energy Nuclear Collisions, Lisbon, Portugal, May 23-27 2016.

29. Z. Xu, “STAR BES-I Highlights and RHIC BES-II Program”, Critical Point and Onset of De-Confinement (CPOD 2016), Wroclaw, Poland, May 30 - June 4, 2016.

30. T. Todoroki, “J/psi RAA and v2 in Au+Au 200 GeV Collisions”, 11th International Workshop on Heavy Quarkonium, Pacific Northwest National Laboratory, Richland, Washington, June 6-10, 2016.

31. J.H. Lee, “Accessing Gluon Sivers’, RHIC/AGS Users’ Meeting, Brookhaven National Laboratory, Upton, New York, June 7-10, 2016.

32. P. Tribedy, “Search for the Chiral Magnetic Effect in U+U & Isobar Collisions”, Workshop on Chiral Magnetic Effect, RHIC/AGS Users’ Meeting, Brookhaven National Laboratory, Upton, New York, June 7-10, 2016.

33. R. Ma, “STAR New Results”, RHIC/AGS Users' Meeting, Brookhaven National Laboratory, Upton, New York, June 7-10, 2016.

34. P. Sorensen, “Ripples of the QGP and the QCD Phase Diagram”, BES Workshop, RHIC/AGS Users' Meeting, Brookhaven National Laboratory, Upton, New York, June 7-10, 2016.

35. P. Sorensen, “What Role do our Attitudes Play in the Composition of our Field”, Workshop on Diversity, RHIC/AGS Users' Meeting, Brookhaven National Laboratory, Upton, New York, June 7-10, 2016.

36. P. Sorensen, “Realizing the Long-Range Plan at RHIC: Collective Dynamics”, RHIC/AGS Users' Meeting, Brookhaven National Laboratory, Upton, New York, June 7-10, 2016.

37. T. Ullrich, "The Glue That Binds Us, Probing Gluonic Matter With the World's First Electron-Ion Collider", Colloquium, Heidelberg University, Heidelberg, Germany, June 14, 2016.

38. P. Sorensen, “Probing the QCD Phase Diagram and Topological Charge at RHIC Ultra-relativistic Heavy Ions”, CERN, Geneva, Switzerland, July 18-20, 2016.

39. R. Ma, “Experimental Summary: Heavy Flavor Production in High Energy Nuclear Collisions”, Strange Quark Matter 2016, Lawrence Berkeley National Laboratory, Berkeley, California, June 27 - Jul 1, 2016.

40. T. Todoroki, “Quarkonium Measurements via the Dimuon Decay Channel in *p+p* and Au+Au Collisions with the STAR Experiment”, Strange Quark Matter 2016, Lawrence Berkeley National Laboratory, Berkeley, California, June 27 - Jul 1, 2016.

41. T. Ullrich, "Status and Prospects of an Electron-Ion Collider", Hard Probes 2016, Montreal, Canada, June 27 - July 3, 2016.

42. T. Ullrich, "The EIC Detector R&D Program", EIC User Group Meeting, Argonne, Illinois, July 7-9, 2016.

43. L. Ruan, “New Physics Ideals Beyond the EIC White Paper”, EIC User Group Meeting, Argonne National Laboratory, Argonne, Illinois, Jul 7-9, 2016.

44. J. Jia, “Towards Uli's Little-Bang Standard Model", Ultra-Relativistic Heavy Ion Workshop, CERN, Geneva, Switzerland, July 18-21, 2016.

45. L. Ruan, “Heavy Flavor/Quarkonium Experiment”, Lecture, Hard Probes 2016, Wuhan, China, September 22, 2015.

FY2015 **U.S. Department of Energy**

Budget Page

ORGANIZATION					Budget Page No.: 1
Brookhaven National Laboratory	**KB0201021 Research - STAR**				
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR					Requested Duration: 12 (months)
Zhangbu Xu					
A. SENIOR PERSONNEL: PI/PD, Co-Pis, Faculty and Other Senior Associates (List each separately with title; A.6. Show number in brackets)		DOE Funded Person-mos.			
1 Flemming Videbaek	Physicist	12.0			
2 Thomas Ullrich	Physicist	12.4			
3 James Dunlop	Physicist	4.6			
4 Zhangbu Xu	Physicist	8.4			
5 Paul Sorensen	Physicist	12.1			
6 Aihong Tang	Physicist	9.1			
7 Lijuan Ruan	Physicist	4.3			
8 Robert Pak	Physicist	12.5			
9 Jeonghun Lee	Physicist	8.2			
10 Wlodzimierz Guryn	Physicist	4.2			
11 Ramiro Debbe	Physicist	10.9			
12 Leslie Bland	Physicist	12.0			
13 Matthew Lamont	Assoc Physicist	6.2			
Others (List individually on Budget Explanation Page)					
13	Total Senior Personnel	116.9	0.0	0.0	$2,055,807
B. OTHER PERSONNEL (show numbers in brackets)		M.m(months)			
1. 3	Post Doctoral Associates	25.9			$172,858
2. 2	Other Professional	0.3			$42,203
3.	Graduate Students				
4. ( )	Undergraduate Students				
5. 2	Secretarial - Clerical	12.5			$100,002
6.	Others (List individually on Budget Explanation Page) (joint appointment)				
Total Salaries and Wages (A + B)					$2,370,870
C. Fringe Benefits (if charged as Direct Costs)	Included in salary band rate				$0
Total Salaries,Wages and Fringe Benefits (A + B + C)					$2,370,870
D.					
Total Permanent Equipment					
E. Travel	1. Domestic (incl. Canada and U.S. Possessions)				$357
	2. Foreign				$5,142
Total Travel					$5,498
F. Trainee/Participant Costs					
	1. Stipends (Itemize levels, types and totals on budget justification page)				
	2. Tuition & Fees				
	3. Trainee Travel				
	4. Other (fully explain on justification page)				
Total Participants		Total Cost			$0
G. Other Direct Costs					
1. Materials and Supplies					$22,725
2. Publication Costs/Documentation/Dissemination					
3. Consultant Services					
4. Computer (ADPE) Services					
5. Subcontracts					$105,030
6. Other Organizational Burden, Space, electric, communications, other)					$483,757
Total Other Direct Costs					$611,511
H. **Total Direct Costs (A through G)**					$2,987,879
I. Indirect Costs (specify rate and base)					
Total Indirect Costs					$1,236,026
J. **Total Direct and Indirect Costs (H + I)**					$4,223,905
K. Amount of any Required cost sharing from Non-federal Sources					
L. **Total Cost of Project (J + K)**					$4,223,905

FY2016 U.S. Department of Energy

Budget Page

ORGANIZATION					Budget Page No.: 1
Brookhaven National Laboratory	**KB0201021 - Research STAR**				
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR					Requested Duration: 12 (months)
Zhangbu Xu					
A. SENIOR PERSONNEL: PI/PD, Co-Pis, Faculty and Other Senior Associates (List each separately with title; A.6. Show number in brackets)		DOE Funded Person-mos.			
1 Flemming Videbaek	Physicist	12.0			
2 Thomas Ullrich	Physicist	12.0			
3 James Dunlop	Physicist	4.6			
4 Zhangbu Xu	Physicist	6.0			
5 Paul Sorensen	Physicist	6.6			
6 Aihong Tang	Physicist	6.0			
7 Lijuan Ruan	Physicist	4.2			
8 Robert Pak	Physicist	0.5			
9 Jeonghun Lee	Physicist	6.0			
10 Wlodzimierz Guryn	Physicist	3.0			
11 Ramiro Debbe	Physicist	4.0			
12 Matthew Lamont	Assoc Physicist	0.6			
Others (List individually on Budget Explanation Page)					
12	Total Senior Personnel	65.4	0.0	0.0	$1,211,519
B. OTHER PERSONNEL (show numbers in brackets)		M.m(months)			
1. 2	Post Doctoral Associates	17.5			$117,793
2.	Other Professional				
3.	Graduate Students				
4. ( )	Undergraduate Students				
5. 2	Secretarial - Clerical	13.2			$109,732
6. 1	Others (List individually on Budget Explanation Page) (joint appointment)				
Total Salaries and Wages (A + B)					$1,439,044
C. Fringe Benefits (if charged as Direct Costs)	Included in salary band rate				$0
Total Salaries,Wages and Fringe Benefits (A + B + C)					$1,439,044
D.					
Total Permanent Equipment					
E. Travel	1. Domestic (incl. Canada and U.S. Possessions)				$4,500
	2. Foreign				$19,500
Total Travel					$24,000
F. Trainee/Participant Costs					
	1. Stipends (Itemize levels, types and totals on budget justification page)				
	2. Tuition & Fees				
	3. Trainee Travel				
	4. Other (fully explain on justification page)				
Total Participants	Total Cost				$0
G. Other Direct Costs					
1. Materials and Supplies					$30,806
2. Publication Costs/Documentation/Dissemination					
3. Consultant Services					
4. Computer (ADPE) Services					
5. Subcontracts					$97,502
6. Other	Organizational Burden, Space, electric, communications, other)				$645,703
Total Other Direct Costs					$774,012
H. **Total Direct Costs (A through G)**					$2,237,056
I. Indirect Costs (specify rate and base)					
Total Indirect Costs					$851,948
J. **Total Direct and Indirect Costs (H + I)**					$3,089,004
K. Amount of any Required cost sharing from Non-federal Sources					
L. **Total Cost of Project (J + K)**					$3,089,004

Budget Explanation

A. Senior Personnel Man/Montl Cost

Staff Listing is shown on the Budget Sheet.

B. Other Personnel

Jiangyong Jia Joint Appointment

C. Fringe and labor burden which are included in the salary band rate

All fringe costs are included in the standard labor rates included in A and B sections. Salary cost data includes salary, paid absence, overtime shift and fringe benefit costs.

D. Capital Equipment

E. Travel

Includes attendance at conferences and visitors to BNL workshops

F. Trainee/Participant Costs

G. Other Direct Costs

Includes: Space, Physics Department Organizational burdens, On-site Housing and Miscellaneous Expenses

	FY 15	FY 16	
	%	%	
Organizational Burden	14.5	14.7	applied to salary with fringe
Electric Distributed	1.18	1.18	applied to salary with fringe

I. Indirect Costs

	FY 15	FY 16	
	%	%	
BNL Material Burden	7.50	7.50	applied to travel, purchases and subcontracts
BNL Common G&A	31.95	32.35	applied to , direct salary plus fringe, organizational burden, purchased goods, material burden, & allocated services
BNL Traditional G&A	8.25	8.25	applied to , direct salary plus fringe, organizational burden, purchased goods, and material burden
BNL LDRD Burden	3.70	2.30	In FY15 = applied to , direct salary plus fringe, organizational burden, purchased goods, material burden, & allocated services In FY16 = base is applied to Total Cost less housing
Composite rate	43.9	43.8	